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Permanent Magnet Generators for Portable Military Power

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ELECTRIC POWER CONSUMPTION is rising at an ever increasing rate in the military as well as in the civilian sector. The complexity and sophistication of new weapons and equipment systems has escalated the Army power consumption from less than 0.1 kW per man during World War I to approximately 2.5 kW per man in today's field operations. Power generation devices to supply this need are varied; they cover the gamut from direct-energy conversion devices to closed Rankine cycle sets, and to the open-cycle gasoline, diesel, and turbine-driven powerplants. Development programs are underway to provide mobile electric power sources with substantially improved reliability and time between overhauls, while maintaining reasonable fuel consumption and low weight and volume in order to retain the ready mobility so vital to today's Army.

TURBO-ALTERNATORS

The turbo-alternator concept is being investigated for mobile powerplants in the 10-300 kW range (1)*. In this concept, a high-speed gas turbine drives an alternator directly without step-down gearing. The alternator output is at a high frequency, typically in the 1200-2500 Hz range, and solid-state power conditioning equipment is utilized to convert the loosely regulated alternator output power to precise user power at 50, 60, and 400 Hz. Experimental 10 kW turbo-alternator sets have been successfully tested, and engineering development test models are under construction. A 100 kW set is in the planning stages. Since the alternators operate at turbine speed, use of wound rotors is ruled out for mechanical reasons. Major consideration is presently being given to the various Lundell and inductor machines with stationary field coils. Recent advances in permanent magnet materials have resulted in renewed interest in permanent magnet (PM) generators for possible use in the turbo-alternator powerplants.

PERMANENT MAGNET ALTERNATORS

Distinct advantages accrue from rotating PM field poles on high-speed generators. This type of construction allows the standard (wound-rotor) rotating field, synchronous generator performance characteristic to be possible at high operational speeds. With the PM alternator, a number of improved electromagnetic performance parameters accrue over those of the stationary coil, high-speed alternators.

MILITARY APPLICATIONS - Permanent magnet generators

*Numbers in parentheses designate References at end of paper.

ABSTRACT

The United States Army MERDC has a continuing program to develop and update a family of portable and/or mobile power generation sets for use by the United States military services. In the past decade, a number of new permanent magnet materials have been developed, far exceeding the energy products of earlier materials. Recognizing the potential of these new materials, and looking toward a new family of lightweight power generation sets, a feasibility study and preliminary design were completed for a 100 kW, 60,000 rpm rotating field permanent magnet generator.

have been used by the military since World War II days. The Army started development of a 150 W unit in 1943 and went into production in 1944 using an early version of Alnico 5. By 1950, the generator line extended through ratings of 12.5 kW, primarily at 400 Hz, using Alnico 5. Precise steady-state and transient voltage regulation and control were not required for this line, and the units provided a simple, rugged, and reliable source of electric power. During the 1950s and early 1960s, the Army investigated the use of Alnico 5 and Alnico 6 for generators which were:

1. To supply precisely regulated power including operation over a 20% voltage range.

2. To supply loads with power factors between unity and 0.8 lagging, and

3. To have both single-phase and three-phase capability in the lower ratings.

These investigations led to the conclusion that such generators were feasible in general military ratings through 5-10 kW, as well as in special applications for even larger ratings. However, the attendant penalties at that time outweighed the advantages. Operational speeds were relatively low and weights generally higher, so that the use of standard wound-rotor machines was more practical. Voltage control required excessive amounts of d-c power or axial movement of the shaft with attendant low speed of response; capacitors could not be used because of the danger of resonance with the load. Thus, PM generators were not included in the family of small military engine-generator sets then under development and standardization.

The Army is presently reinvestigating the military applicability of PM generators because of:

1. Significant improvements in the maximum energy product of permanent magnets during the past few years.

2. A change in the philosophy of the voltage control problem due to the use of static power conditioners.

3. The system improvements accrued as opposed to the penalties resulting from the generally higher transient and subtransient reactances of high-speed solid-rotor, stationary coil alternators.

MATERIAL DEVELOPMENTS - The general trend in the development of PM materials has been one of increasing rate of improvement with time. A general yardstick by which the quality of a permanent magnet is measured is its maximum energy product; this is the maximum value of the product of flux density B (gauss) and field strength H (oersted) which the magnet has available to drive flux through a magnetic circuit. Generally speaking, the size and weight of a PM generator will decrease as the maximum energy product of the excitation magnet increases. In Fig. 1, the maximum energy product of typical permanent magnet materials is shown relative to the time when the materials became available (2). The accelerating trend of improvement is clearly evident. The maximum energy product of samarium cobalt is particularly noteworthy. The value shown of 16 megagauss-oersted is based on the best available data at present, and is apt to be changing rapidly in the future because of the developmental nature of the material. Substantially higher values have been reported, and one manu-

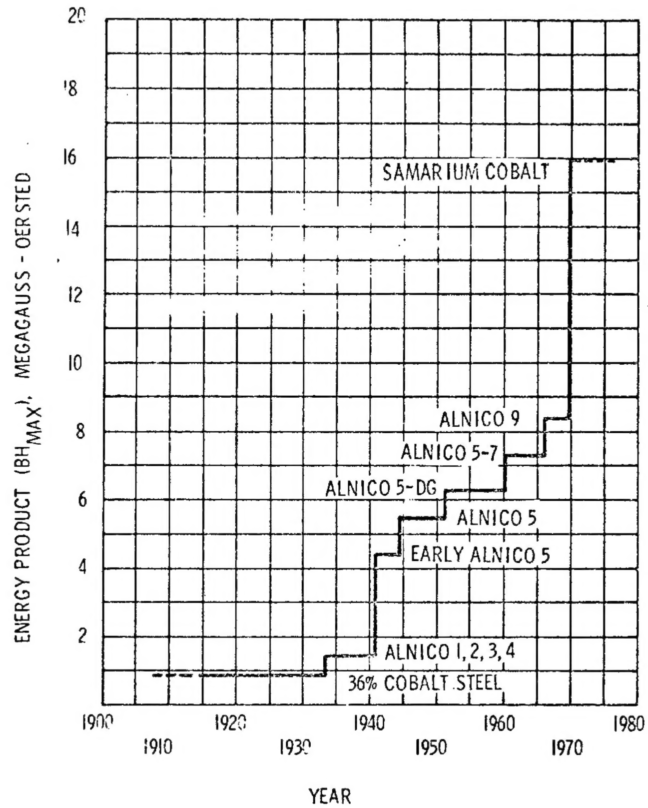

Fig. 1 - Maximum energy products of selected permanent magnet materials

facturer has advertised a maximum energy product of 20 megagauss-oersted.

CHARACTERISTICS - The requirement for close voltage regulation tolerances was one of the major factors ruling out PM generators in the past. The output from the generator was used directly, and inherent voltage regulation was unacceptable. In today's high-speed turbo-alternator application, a static power conditioner placed between the generator and the actual utilization equipment conditions the alternator power, notably frequency and voltage. As a result, the inherent voltage regulation of the alternator has lost its critical aspects although it retains some importance in terms of simplicity of the power conditioner. Further, the newer permanent magnet materials improve inherent voltage regulation due to their decreasing reversible permeability. The reversible permeability of samarium cobalt is substantially less than that of the Alnicos, roughly one-fourth that of Alnico 5, and two-thirds that of Alnico 9.

Stationary coil, high-speed alternators such as the inductor and Lundell machines have long leakage paths and do not provide good damping for transient magnetic flux patterns. As a consequence, they present a high source impedance and commutating reactance to any power conditioning equipment. This, in turn, forces use of oversize alternators, of special circuitry, and/or provisions of energy storage devices such as buffer capacitors. The PM alternator has the short leakage paths of a standard wound-rotor synchronous machine and can be equipped with relatively effective damping means. This greatly reduces the reactance problem normally associated

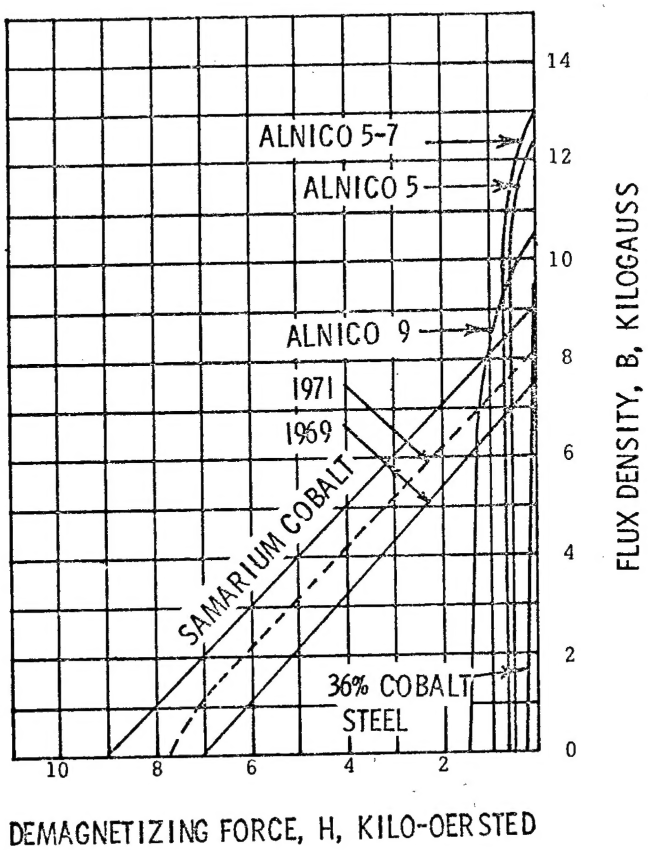

Fig. 2 - Demagnetization curves of selected permanent magnet materials

with high-speed, solid-rotor alternators when matching them to the power conditioner.

If more recent permanent magnet materials are utilized, size and weight of the PM alternators are found to be competitive with other high-speed electrical machinery. In addition, the short-time overload capacity of a machine using samarium cobalt will be high because the demagnetization curve of samarium cobalt is nearly linear in the second quadrant. No permanent demagnetization and loss of output voltage occurs until the very high coercive force of the material is exceeded (in excess of 9000 oersteds). The straight-line demagnetization curve also results in magnets which are inherently air-stabilized. Demagnetization curves of a number of materials including samarium cobalt are shown in Fig. 2 to illustrate this point. The range of data for samarium cobalt reflects the developmental nature of the material at the time of the study; the dotted line illustrates more positive data which became available over a year later.

FEASIBILITY STUDY

DESIGN GOALS - Specific design goals were selected to evaluate the alternator as a candidate for use in the turboalternator family now under development. A target speed of 60,000 rpm with 10% overspeed was selected and a 100 kW output was specified. In order to take advantage of the relatively low commutating reactance of standard synchronous machine construction, a rotating permanent magnet field was specified as was a maximum subtransient reactance of 14%. The power factor rating was set near unity (0.95) easing the voltage regulation problem somewhat, and slanting the alternator toward use with rectifier-inverter or unity power factor cycloconverter power conditioners. Weight was set at 100 lb maximum, giving a very acceptable weight-to-power ratio. Minimum service life between overhauls and without remagnetization was set at 1500 hr, with an eventual 6000 hr requirement looming in the background. For obvious reasons, short circuits on the alternator could not cause permanent demagnetization. Waveshape of the output voltage has only minor importance in view of the use of a power conditioner; the deviation factor was set at 5% maximum. Materials to be considered in the study were the more recently developed magnets such as Alnico 8, Alnico 9, and samarium cobalt. An 8 X 8 (KG to KO_e) linear demagnetization curve was assumed for the samarium cobalt in the study.

ELECTROMAGNETIC DESIGN CONSIDERATIONS - In general, the cross-sectional area of a permanent magnet in a given application is less for a permanent magnet material having a high residual flux density; magnet length (thickness) is less for high values of coercive force; magnet volume is less for high values of energy product. Required magnet volume is an important design consideration where the rotor size must be kept small because of rotor stress and rotor dynamic considerations.

The peak magnetizing force for samarium cobalt magnets is 60,000 oersteds compared to about 3000 oersteds for Alnico 5. Magnetizing equipment to achieve fields of 60,000 oersteds in air gaps of 1/4 in. or more is not standard by any means, for example, a superconducting solenoid is required. This necessitates assembling the rotor with premagnetized, very strong permanent magnets. Special handling-design techniques are required.

Calculated electromagnetic weights are shown in Fig. 3 as functions of the number of rotor poles and the magnetic material. The electromagnetic weight decreases with increasing numbers of poles for all three materials, most significantly for the Alnicos. This trend is caused by the low-residual rotor flux resulting from air stabilization of Alnico rotors. The out-of-stator leakage permeance for designs with fewer poles is small and severe demagnetization occurs when these configurations are air-stabilized. This effect can be reduced by designing the pole heads for higher flux leakage between poles; however, there are associated weight penalties. The curve of electromagnetic weight for the samarium cobalt designs shows little weight variation for the 4-, 6-, and 8- pole designs.

MECHANICAL SUPPORT FOR PERMANENT MAGNETS - The initial design effort indicated a rotor diameter of approximately 3.9 in. was required for a 4-pole rotor with a two-thirds pole embrace and that samarium cobalt was required. The use of the samarium cobalt material reduced the height of the magnets to 0.222 in. resulting in a technically feasible design. This conclusion was based upon a preliminary screening analysis of the stress intensities within a support structure consisting of a 0.2 in. thick cylinder around the rotor, the cylinder having a uniform pressure of 10,700 psi acting upon two-thirds of the circumference. The 10,700 psi pressure load represented

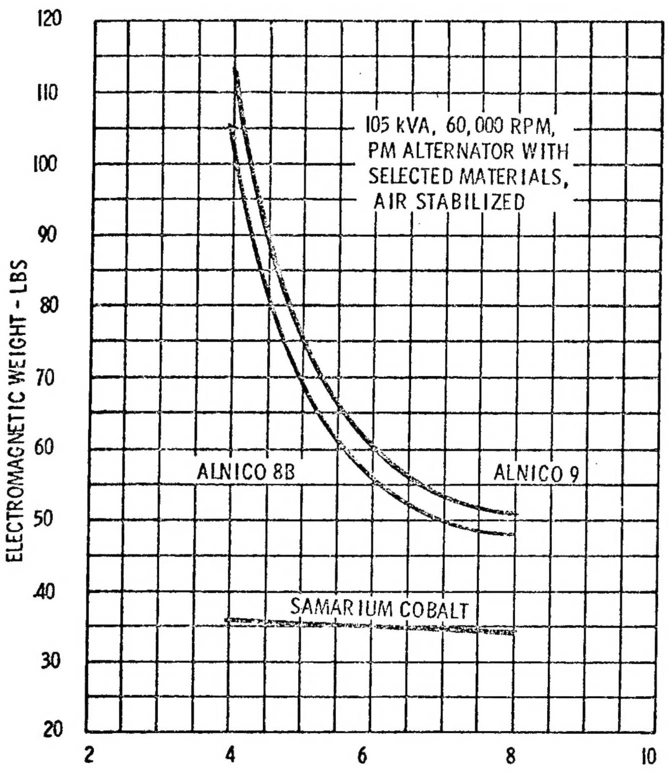

Fig. 3 - Electromagnetic weight versus poles

the centrifugal load of the permanent magnet material; the effect of this centrifugal loading upon the magnet's properties is unknown and could not be factored into the electromagnetic design.

As a result of this preliminary screening, the following criteria for selection of rotor materials were established.

1. A nonmagnetic material and a magnetic material are required which have 0.2% offset yield, and tensile strengths at 700 F equal to or greater than 150,000 and 180,000 psi, respectively.

2. The magnetic material must offer adequate and stable magnetic properties at temperatures up to 700 F with no significant change for 6000 hr.

3. The materials must be capable of being strengthened and bonded together to form a composite structure without a significant loss of strength in the bond, or the materials must be capable of being bonded together and subsequently heat-treated to form a high strength composite rotor.

Sixteen possible candidates were identified and from these Inconel 718 (nonmagnetic material) and 18% nickel maraging steel (Grade 250) were selected. Nominal compositions of these materials are given in Table 1. Tensile properties for fully strengthened conditions are given in Table 2.

PRELIMINARY DESIGN SUMMARY

The preliminary studies did not indicate any apparent advantages, either electromagnetic or mechanical, for a 6- or 8-pole design, and as a result, the 4-pole samarium cobalt generator was chosen for the preliminary design. The electromagnetic design tradeoffs between reactance, losses, rotor outside diameter, and weight are shown in Fig. 4. Synchronous reactance increases with the number of series armature turns which has the effect of reducing the weight of the required magnetic circuit, since less flux is required to generate a given voltage. Losses are reduced primarily as a result of the reduced weight of the a-c armature stack because iron losses predominate at 2000 Hz. The subtransient reactance increases with X_d because of increased leakage reactance. Rotor diameter decreases slightly as X_d increases due primarily to the reduced size of the magnetic circuit.

Fig. 5 shows armature core weight versus armature core loss with the present design point indicated. A decrease of 1 kW in core loss from the present design point would increase alternator electromagnetic efficiency from 93.5% to 94.3%, but would increase alternator electromagnetic weight by 24 lb.

The short circuit armature current of 2.8 per unit is well below the 6.0 per unit current required for demagnetization. Armature short circuit transient currents of 16.2 per unit were calculated, but the demagnetizing magnetomotive force from this transient current can be partially blocked by transient currents flowing in a conductive metal surrounding the magnets.

Voltage regulation of the alternator from no load to rated

Table 1 - Nominal Composition of Rotor Materials

	Inconel 718	18% Ni Maraging Steel	Composite Alloy
Al	0.6%	0.1%	0.35%
B	0.006 max.	0.003	0.0045
C	0.08 max.	0.03 max.	0.05 max.
Cb	5.12		2.6
Co	1.00 max.	7.5	4.4
Cr	19.		9.5
Fe	18. (bal.)	68. (bal.)	43. (bal.)
Mn	0.35 max.	0.10 max.	0.22 max.
Mo	3.	4.8	3.9
Ni	53.	18.5	35.5
P	0.015 max.	0.01 max.	0.01 max.
S	0.015 max.	0.01 max.	0.01 max.
Si	0.35 max.	0.1 max.	0.22 max.
Ti	0.8	0.4	0.6

Table 2 - Tensile Properties of Rotor Materials, Fully Strengthened by Annealing And Aging

	Inconel R. T.	Alloy 718 600 F	18% Ni R. T.	Maraging Steel 700 F
0.2% offset strength, psi	174,500	156,000	253,600	224,100
Tensile strength	198,000	183,500	262,800	235,200
Elongation	12.9%	16%	11.0%	12.0%
Reduction of area	10.9%	34%	56.1%	56.1%

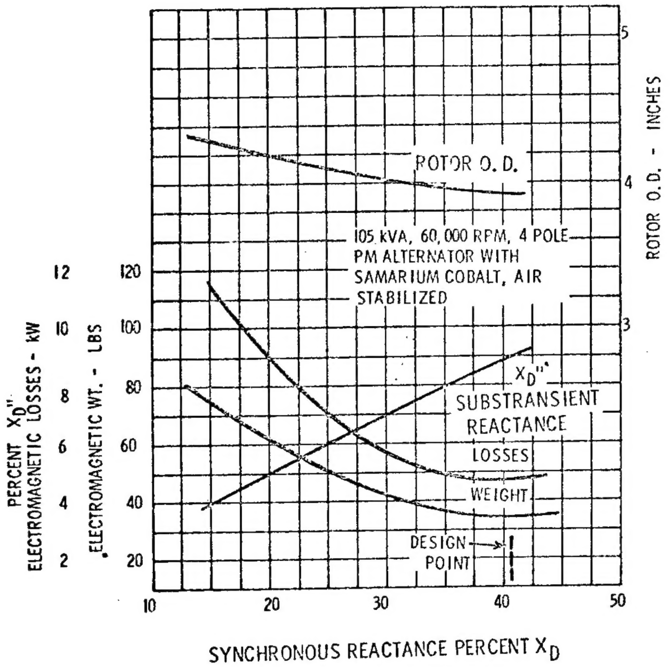

Fig. 4 - Design tradeoff data

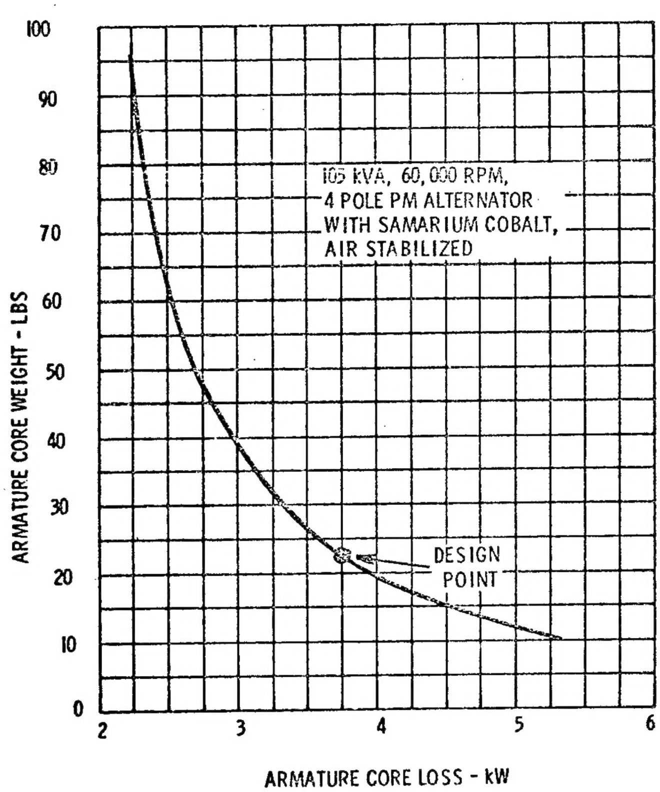

Fig. 5 - Armature core weight versus loss

loads is 17.8%. The effect on terminal voltage of decreasing the inductive power factor is given in Table 3. The voltage at a given power factor is found by multiplying the voltage at rated load and power factor (0.95 lagging) by the corresponding voltage reduction factor Kr.

The estimated losses and weights of the PM generator are presented in Tables 4 and 5. These tabulated losses are based

Table 3 - Voltage Versus Power Factor

Power Factor	Voltage Reduction Factor
0.95	1.000
0.90	0.943
0.85	0.908
0.80	0.880

Table 4 - Permanent Magnet Generator Predicted Losses

	Into a Linear Load, W	Into a Full Wave Bridge, W
Electromagnetic losses		
Armature core	3780	3780
Armature teeth	1380	1380
Armature windings	1132	2004
Rotor pole face	685	1427
Subtotal	6997	8591
Electromagnetic efficiency	93.5%	92.1%
Mechanical losses		
Windage (at 14.7 psia)	3300	
Rolling element bearings and labyrinth seals	2240	
Subtotal	5540	
Total PMG losses	12537	14131
Overall efficiency	88.9%	87.6%

Table 5 - Permanent Magnet Generator Predicted Weight

Armature iron	32.0 lb
Armature wire	1.5
Armature insulation	0.6
Stator frame and end bells	18.0
Bearing support and seals	3.3
Bearings	0.9
Rotor	33.5
Total weight	89.8 lb

upon a design rotative speed of 60,000 rpm with the rotor at atmospheric pressure. Ball bearing losses are indicated in Table 4; with longer life fluid film bearings, losses can range from 2-1/2 to 14-3/4 kW depending on the oil type and temperature. These added film bearing losses are not a result of the particular PM alternator concept, rather they are for any similar sized high-speed machine utilizing fluid film bearings. Differences in windage loss calculation methods result in a range of error covering 3.3-4.0 kW; the 3.3 kW value is shown in Table 4.

The conceptual scheme of the 100 kW PM generator is shown in Fig. 6. Being a preliminary design and not constrained to operate with a specific prime-mover or system, the frame, end bells, coolant passages, and connections are pri-

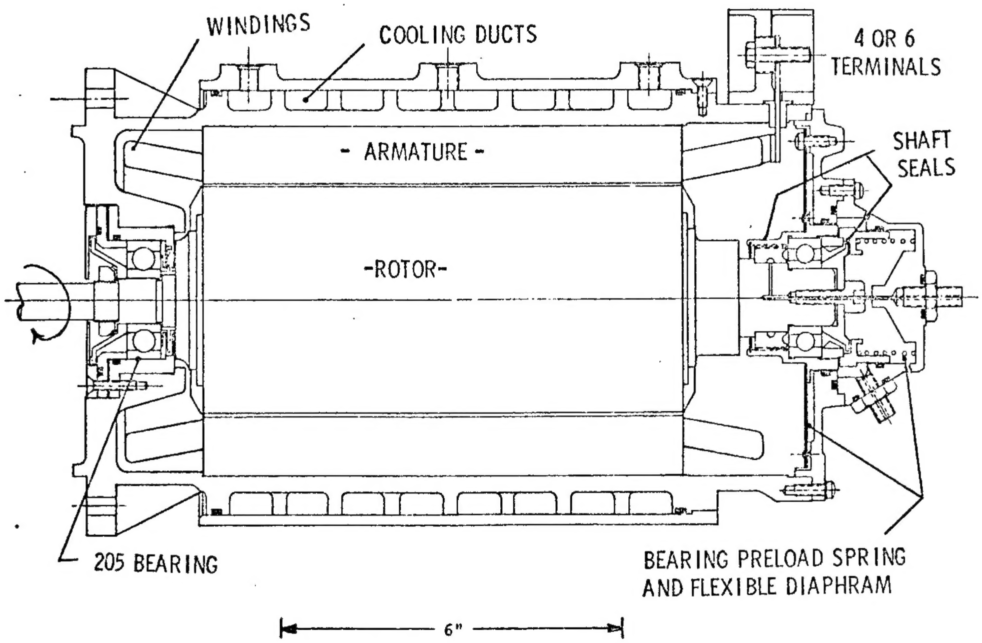

Fig. 6 - Permanent magnet generator conceptual design

marily conceptual. These areas will be subject to detail definition for a specific system.

Since no rotor coolant is provided, the rotor pole face losses and windage losses will be removed from the rotor outer diameter and air gap by convection and radiation, being transported to the stator teeth and out the ends of the air gap to the internally exposed portions of the frame. By skewing the stator slots, an axial flow will be assured in the gap. Also, flow control devices utilizing the kinetic energy stored in the gas can be included to enhance this flow. Copper losses, iron losses, and as much as one-half the windage and pole face losses will be transferred to the stator outside diameter by conduction through the armature stack. The resulting hot-spot temperatures in the alternator rotor will not be more than 300 F greater than the coolant temperature. Magnet temperatures as high as 400-450 F are possible; the degradation the samarium cobalt might experience as a result was unknown at the time of the study and will require future evaluation. Average winding temperatures will not be more than 200 F greater than the coolant temperature. However, without axial flow of gas in the gap, these temperatures could rise another 160 F and 50 F, respectively.

Analysis of rotor dynamics and bearing loads indicates that a support structure can be designed to assure no critical speeds within 20% of either side of the design speed. Analysis indicates that the selected 205 size rolling element bearings may only have a 3300-3800 hr service life. If the 6000 hr goal is to be met, the use of the higher loss hydrodynamic film bearings becomes necessary.

The electromagnetic materials used are those found in any typical military aerospace electrical power generator with three exceptions: the samarium cobalt magnets, the special rotor structural steels, and the 0.004 in. thick Hiperco 27 armature laminations, the latter being selected to minimize core losses without undue addition of fabrication costs.

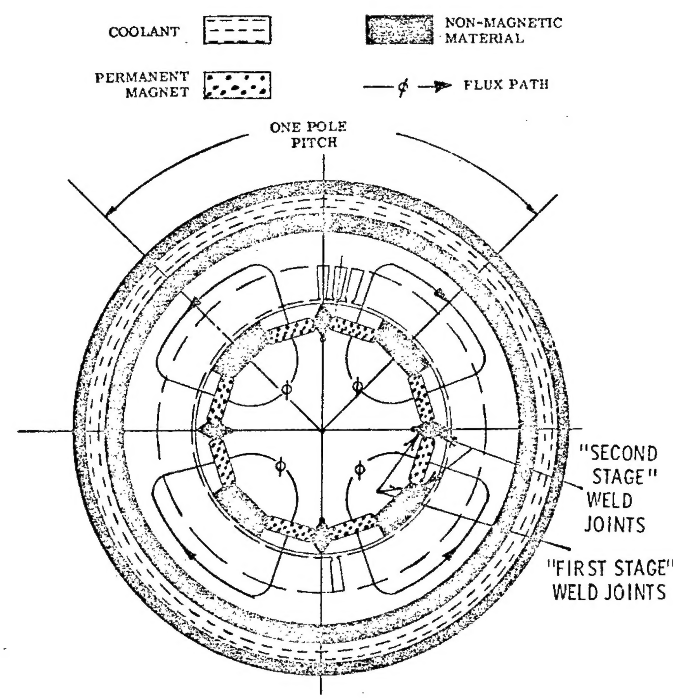

Fig. 7 - Cross section of 4-pole PM generator

ROTOR DESIGN DETAILS

DESCRIPTION OF MAGNET SUPPORT STRUCTURE - The locations of the permanent magnets in the poles are illustrated in Fig. 7. Each pole consists of two magnets located symmetrically about the axis of the pole; two magnetic pole

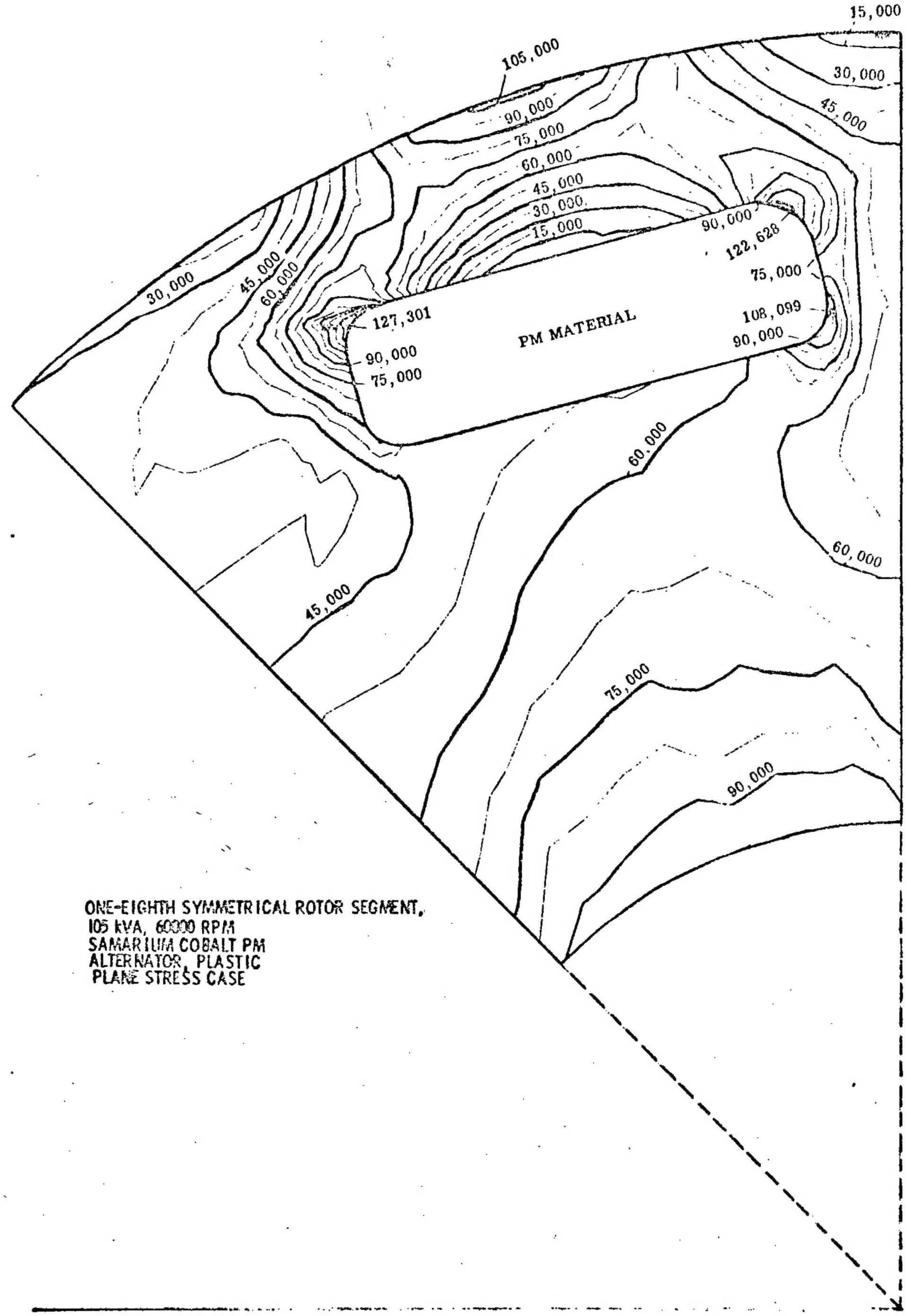

Fig. 8 - Rotor equivalent stress

heads cover them. Nonmagnetic supports are located between magnets and between adjacent poles. The clearance space around the permanent magnet is filled with an epoxy adhesive. From a magnetic design standpoint, only one magnet is required for each pole; however, that simple arrangement produces excessive stress intensities in the rotor around the corners of the magnet penetration. The excessive stress intensity is partially a result of the centrifugal load of the magnet on the pole head. The pole head must restrain the magnet by a combination of shear, moment, and tensile forces in the thin sections of the structure around the corners. The combined mass of the materials is effectively reduced by using a two-magnet configuration as shown.

ROTOR STRESS ANALYSIS - The stress intensities within the rotor were calculated using a finite element computer program for plane elastic-plastic problems based on the deformation theory of plasticity and on the finite element displacement method. A plane perpendicular to the axis of rotation was examined by approximating the actual shape of the rotor with an assemblage of triangular elemental areas. It was only necessary to generate a network of elements for one-eighth of the plane, since the rotor has a symmetric and periodic distribution of form and stress with respect to the center of any one of the four poles. Several cases were investigated in order to demonstrate the effects of plastic flow of the material, differential thermal expansion of the material, and the

quality of the epoxy adhesive. The solution most representative of the actual streses is illustrated in Fig. 8 for the equivalent Von Mises stress. The sharpness of the isostress lines is a result of computer controlled plotting.

The highest stress intensities occur in the upper corners of the magnet penetration. In Fig. 8, these maximum equivalent stresses are 127,301 and 122,628 psi. A small portion of the metal around three corners of the penetration is in a plastic state of stress–proportional limits of 112,000, 85,000 and 112,000 psi were used for the maraging steel, weldment composite, and Inconel 718 materials, respectively.

Unfortunately, the high stresses occur in the weldment zone between the magnetic and nonmagnetic material. Definitive data for proportional limits and stress-strain curves for the composite alloy in the weld zone do not exist and are extremely difficult to obtain. However, the stress attenuates rapidly in the weldments and the average stress intensity along each weldment is low, typically 53,000-60,000 psi at 60,000 rpm. Only the locations on the immediate boundary of the penetration have a stress intensity above the 0.2% off-set yield strength (115,000 psi) of the materials. Also, with more rounding of the corners, with relocation of the magnets to minimize stresses, or with notching to relieve or relocate the corner stresses, it may eventually be possible to reduce the stress intensities to less than 130 ksi at 10% overspeed.

MATERIAL STRENGTHS - In general, the mechanical integrity of the support system for the magnets depends upon the strength of the weldments and their ability to deform plastically. Such data for these weldments has to be generated in the future. Until then, final conclusions relative to the mechanical integrity of the support system for the magnets cannot be positively made. However, related supplier data are available, which allow some judgments to be made relative to the integrity of the structure.

1. Data for Inconel alloy 718 was obtained from material annealed at 1950 F for 2 hr and aged at 1400 F for 10 hr plus 1200 F for 10 hr. Electron beam welds made in 1/4 in. plate which had been heat treated in this manner (no post weld heat treatment) were found to have yield and tensile strengths of 115,000 and 137,000 psi, respectively. Gas-tungsten arc welds in annealed plate with post weld heat treatment were found to have yield and tensile strengths of 149,000 and 173,000 psi, respectively.

2. The 18% nickel maraging steel is strengthened by annealing at 1500 F and aging at 900 F. Electron beam welds made in material which had been heat treated in this manner (no post weld heat treatment) were found to have yield and tensile strengths of 183,000 and 190,000 psi, respectively. Electron beam welds made in material which had been heat treated in this manner and aged after welding were found to have yield and tensile strengths of 249,000 and 260,000 psi, respectively.

The welding and heat treatment data available for such materials indicate that two procedures might be applicable to form the rotor weldments. The first procedure consists of forming the weldment from fully heat-treated materials without subsequent heat treatment. Electron beam welds would be used to minimize the heat affected zone. From the previous data, a yield strength of 115,000 psi could be anticipated for the heat affected zone within the Inconel alloy. Similarly, a yield strength of 183,000 psi could be anticipated for the heat affected zone within the 18% nickel maraging steel. The strength of the composite alloy in the joint cannot be estimated at this time. A survey of the literature was made and several experts were consulted on this specific weldment, but virtually no experimental data was available.

The other (preferred) procedure for forming weldments of Alloy 718 and 18% nickel maraging steel consists of welding fully annealed materials and post weld heat treating. From previous data, a yield strength of 149,000 psi could be anticipated for the Inconel alloy and a yield strength of 250,000 could be anticipated for the 18% nickel maraging steel. The strength of the composite alloy within the weldment again cannot be estimated. It must be determined with sample welds before the final determination of feasibility can be made.

SUMMARY

Samarium cobalt permanent magnet material was found to be applicable to the generator investigated. While this material is adequate electromagnetically, its low mechanical strength makes it necessary to utilize a unique rotor structure capable of both containing and supporting the magnets. Improved magnet properties, notably flux density, would be advantageous to the mechanical and electromagnetic characteristics of the design. Latest available magnet data will have to be evaluated prior to preparation of the final alternator design since new developments should continue to emerge.

The rotor will consist of the magnets, a magnetic steel core and pole face, and nonmagnetic steel webs to support the poles. The nonmagnetic and magnetic steels will be (electron beam) welded and then heat treated prior to final machining of the rotor structure. The permanent magnets are installed after machining. Within the operating speed range of the alternator, stress levels in the heat treated steels outside of the weld zone are safe; those within the weld zone appear tolerable. The mechanical properties of the alloy formed in the weld zone are not known and can only be estimated. Since the maximum stress areas occur within weld zones, development of welding procedures and tests of the resulting welds will be required.

Analysis of rotor dynamics indicates that the critical speeds will not fall within 20% of the design operating speed. The alternator life is limited to 3300-3800 hr if rolling element bearings are used. The cooling system utilizes a liquid coolant around the frame of the alternator. However, a combined cooling system using both internally circulating air and the liquid coolants is feasible and reduces the estimated hot-spot temperatures to safe levels for long life.

Major problem areas detected during the study or anticipated during subsequent efforts to develop a PM alternator are:

1. Proposed welding and heat treatment methods may not develop the high strengths required in the weldments. This

will require relocation of the magnets and possible redesign of the rotor and stator.

2. The thermal and centrifugal effects on the magnet characteristics are unknown, and may cause the first machine to be derated from its calculated design output if the magnets degrade under operating stress and temperature.

3. Rolling element bearings will be the limiting factor in the service life of the PMG. This may require higher loss fluid film bearings.

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